EVALUATION OF DIFFERENT METHODS AND MODELS FOR BACKCALCULATING CONCRETE PAVEMENT PROPERTIES BASED ON DENVER INTERNATIONAL AIRPORT DATA

By:
Dulce Rufino, Jeffery Roesler, and Ernest J. Barenberg

Department of Civil and Environmental Engineering
University of Illinois at Urbana-Champaign

PRESENTED FOR THE 2002 FEDERAL AVIATION ADMINISTRATION AIRPORT TECHNOLOGY TRANSFER CONFERENCE

05/02

EVALUATION OF DIFFERENT METHODS AND MODELS FOR BACKCALCULATING CONCRETE PAVEMENT PROPERTIES BASED ON DENVER INTERNATIONAL AIRPORT DATA

Dulce Rufino[1]
Jeffery Roesler [2]
Ernest Barenberg [3]

This paper presents a backcalculation study of pavement properties based on 277 deflection basins obtained from Denver International Airport (DIA). The DIA runway pavement structure is comprised of a Cement Treated Base (CTB) between the concrete slab and subgrade. Different layer models have been tested assuming the pavement foundation is a dense liquid. The models used in the analysis were one plate and one elastic layer over dense liquid, and two plates and two elastic layers over dense liquid, for both bonded and unbonded conditions. As a result, one of the focuses of this paper is the effect of slab modeling (number of layers, interface condition, and model type) on backcalculated pavement properties. This paper also deals with effect of different backcalculation methodologies, which are related to the properties of the deflection basin. One iterative and one closed-form backcalculation techniques were tested against a database backcalculation technique developed specifically for this study. This database-type backcalculation program was developed using Visual Basic to backcalculate pavement properties for different models, methodologies and number of sensors. This program automatically creates DIPLOMAT input files, runs the program, extracts surface deflections, and selects the pavement properties that best reproduce the measured deflection basins for different backcalculation methodologies. The backcalculated pavement properties are based on an error minimization process.

INTRODUCTION

Over the last twenty years, nondestructive testing (NDT) using the Falling Weight Deflectometer (FWD) has become a common testing procedure to structurally evaluate in-service pavements. Since stresses in concrete pavements cannot be directly measured, pavement engineers have relied on measured deflection profiles at the pavement surface for use in backcalculation. Backcalculation of pavement properties is a useful tool not only to evaluate structural condition of in-service pavements but also to characterize layer properties as inputs into available numerical or analytical programs. All backcalculation procedures estimate pavement properties by matching measured and calculated pavement responses.

Pavement engineers have developed many different backcalculation procedures and programs to interpret FWD deflection measurements such as AREA method for flexible pavements (Hoffman and Thompson, 1981), AREA method for rigid pavements (Ioannides *et al.*, 1989, Ioannides, 1990, and Barenberg and Petros, 1991), ILLI-BACK (Ioannides, 1994), graphical solution using IILI-SLAB (Foxworthy and Darter, 1989), use of regression analysis to solve AREA method for rigid pavements (Hall, 1992, and Hall *et al.*, 1996), use of best fit algorithm to find radius of relative stiffness (Hall *et al.*, 1996, and Smith *et al.*, 1996), ELMOD (Ulidtz *et al.*, 1987, MODULUS (Uzan *et al.*, 1989), WESDEF (Van Cauwelaert *et al.*, 1989), among others. Each of these procedures relies on different techniques and pavement models. The following paragraphs discuss application of some of these procedures for backcalculation of concrete pavement properties.

[1] Graduate Research Assistant; phone 217-333-7311; rufino@uiuc.edu
[2] Assistant Professor; phone 217-265-0218; jroesler@uiuc.edu
[3] Emeritus Professor; phone 217-398-9061; ejbm@uiuc.edu
University of Illinois at Urbana-Champaign, Department of Civil and Environmental Engineering, 205 N. Mathews Ave., Urbana, IL 61801-2352

Different backcalculation methodologies and the FWD sensor configuration (number and location) affect backcalculated pavement properties. The type of pavement model selected affects the backcalculated layer properties because it leads to different predicted surface deflections. There are many issues related to the theoretical modeling of concrete pavements such as the subgrade model, modeling of the layers on top of subgrade and their interface condition, slab size, etc. This paper discusses effects of different models on backcalculated concrete pavement properties, as well as effect of different methodologies and sensor configurations. A comparison between three different approaches is presented: AREA, Actual Area and individual deflections.

BACKGROUND ON BACKCALCULATION OF CONCRETE PAVEMENT PROPERTIES

One important issue of concrete pavement analysis is how to model the slab foundation or subgrade. The two most common models used for concrete pavement foundations characterization are the dense liquid and elastic solid, proposed by Winkler (1867) and Boussinesq (1885), respectively. A real soil, however, behaves neither as a dense liquid nor as an elastic solid, as discussed by Darter *et al.* (1995). Its behavior lies between these two models. A soil will sometimes behave closer to one of these models and other times closer to the other depending on the other layer properties. In the dense liquid model, the real foundation is replaced by a set of linear springs that do not interact with one another. Each spring deforms in response to the pressure applied over it, leaving the others unaltered if no pressure is applied over them. A pressure over any point in the foundation is proportional to the displacement at that point alone, and the constant of proportionality is called modulus of foundation reaction. In contrast, in the elastic solid model, also called "Boussinesq's half-space", the soil is characterized as a homogeneous, linearly elastic, and isotropic solid, which extends horizontally to infinity and has a semi-infinite depth. In this case, the soil is characterized by its elastic properties: elastic modulus and Poisson's ratio. According to this model, the displacement at a given point depends not only on the stress over it but also on the stress over the neighboring points. The Winkler foundation (dense liquid model) has historically been more utilized for concrete pavement analysis. Although elastic solid modeling has some advantages over the Winkler foundation, it typically overestimates subgrade elastic modulus and produces singularities at joints or cracks (Ioannides, 1991). An extensive study by Khazanovich and Ioannides (1993) on different subgrade models concluded that the dense liquid foundation model is currently the most advantageous model to reproduce edge responses, which is the most critical load location for stress. For these reasons, dense liquid model will be used herein to characterize the subgrade behavior.

Concrete pavements are usually comprised of at least two layers on top of the subgrade. Each of these layers can be modeled as a plate (vertical compressibility and transverse shear deformations are ignored) or elastic layer. It is very common that concrete and asphalt pavement layers are modeled as plate and elastic layers, respectively. According to Ioannides and Khazanovich (1992), the main reason for this preference is because Burmister modeled the subgrade as elastic solid for flexible pavement analysis. However, the layered elastic analysis modeling is not only associated with elastic solid foundation, as Van Cauwelaert demonstrated in 1990 by modeling the slab-on-grade problem using an elastic layer over dense liquid formulation (Ioannides and Khazanovich, 1992). Therefore, a plate over an elastic solid and elastic layer over dense liquid can be modeled, even though these are not common approaches.

Different backcalculation methodologies have been developed to estimate pavement properties. A common approach is to use an error minimization scheme to match measured and predicted deflections. Many backcalculation programs are based on the 'goodness of fit' between the measured and predicted deflection profile (Mahoney *et al.*, 1989). One disadvantage of this approach is that it requires n-deflections to be compared, and depending on the number of sensors used to measure the deflection profile, inaccuracies in deflection measurements will result in large errors in layer properties. Hoffman and Thompson (1981) developed a methodology for flexible pavement backcalculation that requires only one parameter: the area of the deflection basin divided by the maximum deflection (D0) or the AREA method. This method gained popularity for backcalculation of concrete pavement properties, once Ioannides *et al.* (1989) recognized the existence of a unique relationship between AREA and radius of relative stiffness, ℓ, for a given radius of applied load. Based on this finding, they proposed a closed-form backcalculation procedure for rigid pavements. Ioannides (1990) provides more detail about the origin of this closed-form procedure, which was based on principles of dimensional analysis. The existence of a unique relationship between AREA and ℓ greatly simplifies the backcalculation procedure for concrete pavements, because once the radius of relative stiffness is known, closed-form solutions can be used to estimate foundation properties.

Ioannides *et al.* (1989) classified the existing different techniques at that time into two main categories: iterative and database. Iterative procedures use a search optimization routine linked to a program for structural analysis of pavement responses to find the set of pavement parameters that better reproduce the measured responses. In contrast, database procedures are based on a priori calculated pavement responses for a variety of possible combinations of pavement properties and structures. The database approach can be used to interpolate pavement properties of similar pavement structures. Therefore, it is mandatory to know the spectrum of pavement properties (thickness and moduli values) used to develop the database, since the backcalculated results are valid only within the range of pavement properties used to develop the database. Some researches have used a graphical interpretation of the database results, such as Foxworthy and Darter (1989). Their graphical solution allows for backcalculation of slab modulus of elasticity and subgrade k-value for a variety of temperatures, using the AREA term and the maximum deflection as an input.

Ioannides *et al.* (1989) closed-form backcalculation technique uses the unique relationship between AREA and the radius of relative stiffness. Once the radius of relative stiffness is known, Westergaard's (1926) or Losberg's (1960) maximum deflection solution for interior loading can be used to backcalculate pavement properties. Westergaard's solution is used to estimate the subgrade k-value, whereas Losberg's equation is used to estimate the subgrade modulus of elasticity. Once the subgrade properties and radius of relative stiffness are known, the slab property can also be determined. This approach has been coded in a computer program called ILLI-BACK by Ioannides (1990) and modified in 1994 (see Ioannides, 1994). Hall (1992) developed equations using regression analysis to obtain the radius of relative stiffness from AREA for different sensor configurations. Later, Hall *et al.* (1996) used a closed-form approach called 'best fit', which consist of minimizing the error function between measured and predicted deflection profile with regard to k-value and ℓ. This procedure has been coded in a program called ERESBACK 2.0.

Artificial Neural Network (ANN) training has also been used to interpret results from databases of deflection profiles to estimate pavement properties. Khazanovich and Roesler (1997) developed a program called DIPLOBACK for backcalculation of moduli values of multilayer pavements based on ANN. ANN has also been applied along with dimensional analysis to backcalculate joint properties from FWD testing (Ioannides *et al.*, 1996). The advantage of using ANN and dimensional analysis together is that they both reduce the database size necessary to accurately estimate pavement properties.

Several programs have been developed based on Burmister elastic layer solutions, but only DIPLOMAT can model pavement layers as plates, springs and/or elastic layers. One disadvantage of DIPLOMAT is that joints cannot be modeled because layers are assumed infinite in the horizontal direction. To analyze more complex conditions, such as multiple slabs and simultaneous effect of wheel and temperature loadings, programs, such as ILLI-SLAB (Tabatabaie and Barenberg,1978; Ioannides,1984; Korovesis,1992; and Khazanovich,1994) can be employed. DIPLOMAT and ILLI-SLAB have different solution techniques: the former uses numerical integration techniques, whereas the later uses the finite element method. DIPLOMAT was developed by Khazanovich and Ioannides (1995), which is an extension of elastic layer and plate theories. DIPLOMAT can accommodate up to five layers, in addition to a rigid layer. The subgrade can be analyzed using the two most widely used models: dense liquid and elastic solid.

Although ILLI-SLAB is one of the fastest available tools to analyze the effects of slab-size, load transfer efficiency, and simultaneous temperature and wheel loading in concrete pavements, it requires significantly more time to analyze the same case then programs like DIPLOMAT. In addition, DIPLOMAT can model elastic layers, whereas ILLI-SLAB can only model plates. As the focus of the current paper is to analyze different methodologies and pavement models disregarding the effects of slab-size and temperature, DIPLOMAT was chosen as the program to generate a database of calculated deflections based on a factorial of pavement layer properties. In addition, there is no iterative-based backcalculation program that uses ILLI-SLAB as the engine, whereas recently Kothandram and Ioannides (2001) developed one called DIPLODEF that uses DIPLOMAT as the engine. Kothandram and Ioannides (2001) used the WESDEF optimization search routine, which was developed by Van Cauwelaert *et al.* (1989).

RESEARCH APPROACH

Heavy Weight Deflectometer (HWD) pavement evaluation tests have been performed at Denver International Airport since 1995. These data are available at the FAA Airport DIA Pavement Database Website at http://www.airtech.tc.faa.gov/DENVER/. A total of 277 measured deflection basins were selected from the tests performed within the instrumented section at DIA for pavement evaluation purpose. The pavement evaluation test locations are shown in Figure 1. A seven-sensor configuration was utilized on the HWD, with each sensor spaced at 12-inch centers. The instrumented section at DIA consists of 16 slabs (20-ft long by 18.75-ft wide), approximately 400 ft from the end of runway 34R-16L threshold. The design pavement cross-section is displayed in Figure 2. Although the slab thickness was designed for 17 in. of concrete, the actual thickness is closer to 18 in based on coring information. Therefore, the average pavement thickness was assumed to be 18 in for the backcalculation analysis. Pavement instrumentation details at DIA can be found in Dong and Hayhoe (1999), Brill (2000) and Rufino *et al.* (2001).

During construction, a bond-breaker was placed between the slab and the cement treated base (Harrison, 1997). Figure 3 shows a comparison between measured strain at the top and bottom collected from paired strain bars placed in one of the instrumented slabs, as a result of actual aircraft pass. It is observed more compressive strain at the top than tensile strain at the bottom. Top and bottom strains would be similar in magnitude if there were no friction between the base and slab. The strains at the bottom are about half of strains at the top suggesting some level of friction between slab and base that has driven the neutral axis of the section deeper.

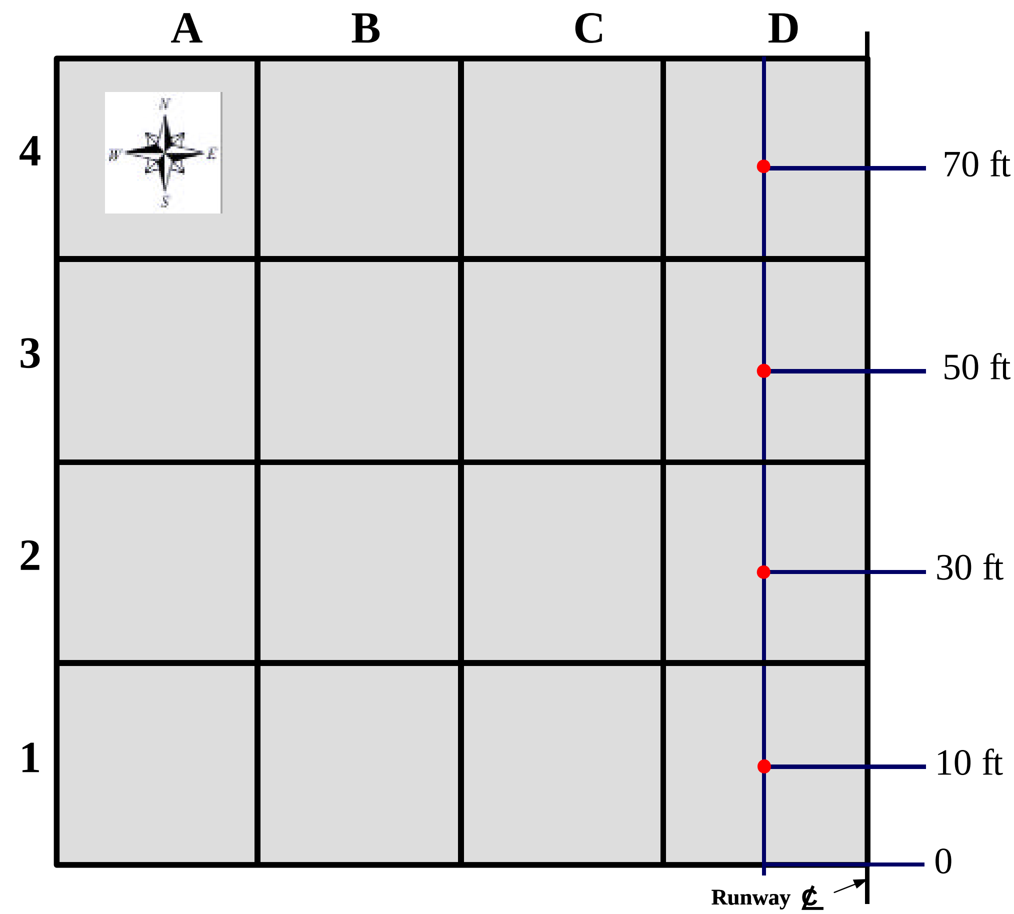

Figure 1. Location of HWD pavement evaluation tests performed at DIA

Due to the unknown level of bonding between the base and slab, the backcalculation procedure must incorporate this parameter in order to reproduce more realistic layer properties. Different structural models with varying interface conditions were tested, as shown in Figure 4. Six separate models over a dense liquid foundation were evaluated through backcalculation: a single elastic layer, a single plate, two elastic layers bonded and unbonded, and two plates bonded and unbonded. DIPLOMAT has been used to test these different pavement models. Since DIPLOMAT does not accept two consecutive plates, the transformed layer concept developed by Ioannides *et al.* (1992) was used to convert two plates into one.

The simplest approach to backcalculate pavement properties is to match calculated and measured sensor deflections. However, this is more time-consuming than matching a single parameter, such as AREA. Another parameter, Actual Area of deflection basin, was also used as the matching parameter. In addition to the pavement model and deflection parameter utilized, the effect of number of sensors selected for the backcalculation process was also evaluated.

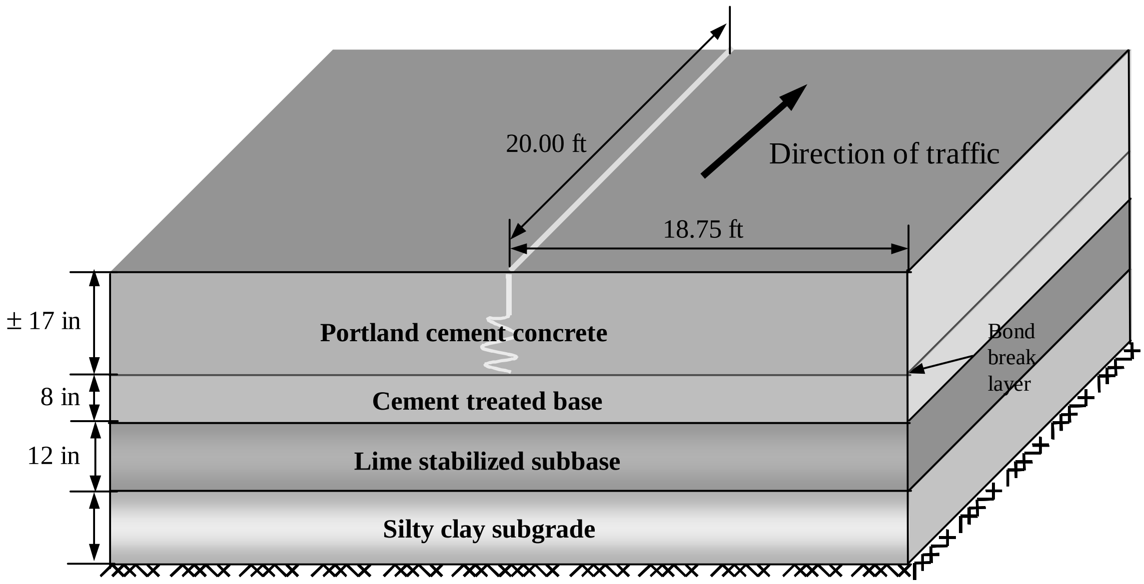

Figure 2. Designed pavement structure at DIA

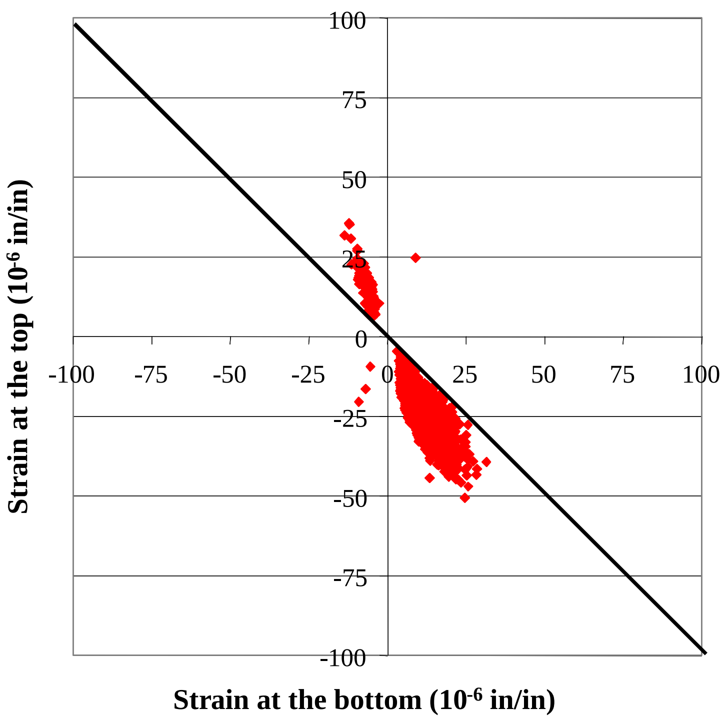

Figure 3. Comparison between strain at the top and bottom at DIA

A Visual Basic (VB) program called DATABACKDIPLO was developed to test all different models, methodologies and sensor configuration. This VB program is a backcalculation program based on a database technique. It generates and runs DIPLOMAT for a factorial of layer properties, extracts surface deflections, and selects the pavement properties that best reproduce the measured deflection basins for all three aforementioned backcalculation methodologies. The backcalculated pavement properties were selected based on an error minimization process between the calculated and measured deflection parameters, depending on the methodology being tested.

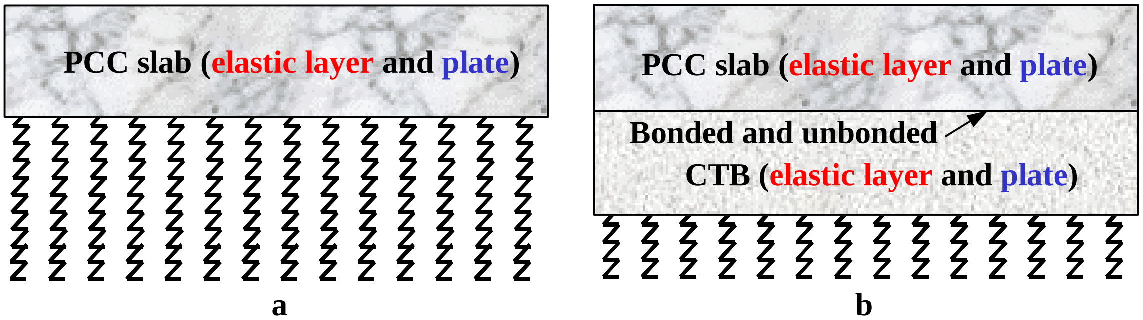

Figure 1. Different tested structural models

The following lists the three deflection basin parameters used in this analysis along with how the error minimization scheme was completed:

AREA and Actual Area

$$ERROR_m = \left| \frac{A_{HWD\,m} - A_{DIPLO\,m}}{A_{HWD\,m}} \right| \quad \textbf{(1)}$$

Where,

m=number of sensors, which varies between 2 and 7 for analysis of area-related methodologies

$ERROR_m$ = error between measured and calculated deflections for m sensors

A_{HWDm} = measured A-term (see note)

A_{DIPLOm} = calculated A-term (see note)

Note. The area of the measured or calculated deflection basin is estimated by trapezoidal rule applied to (m-1) areas. The A-term refers to the measured or calculated deflection basin area only when applying Actual Area methodology and when applying the AREA methodology the actual area is divided by the maximum deflection, D0.

Individual Deflection

$$ERROR_n = \frac{\sum_{i=1}^{n} \left| \frac{D_{HWD\,i} - D_{DIPLO_i}}{D_{HWD_i}} \right|}{n} \quad \textbf{(2)}$$

n=number of sensors

$ERROR_n$=error between measured and calculated individual deflections for n sensors, where n varies between 1 and 7

D_{HWDi}=individual deflections measured under each HWD sensor
D_{DIPLOi}=individual deflections computed from DIPLOMAT at each HWD sensor location

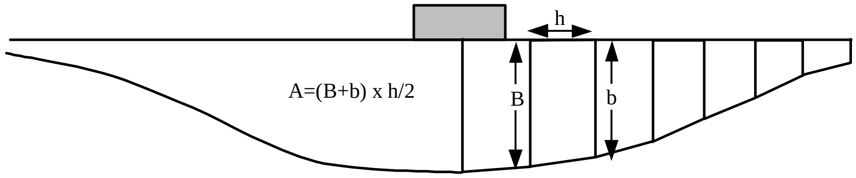

Figure 5. Estimation of basin area using trapezoidal rule

The factorial of runs performed in DIPLOMAT is shown in Figure 6. The total number of cases run was approximately 170,000. Once the forward-calculated deflections were completed, the error minimization process was applied to each database according to the pavement model, backcalculation parameter, and number of sensors being tested. When testing the AREA methodology, the radius of relative stiffness was obtained from the minimization process and then used in the Westergaard interior load equation (1926) to find the k-value based on the peak sensor deflection (D0). Once k-value and the radius of relative stiffness were known, it was possible to find the slab modulus of elasticity from the radius of relative stiffness equation.

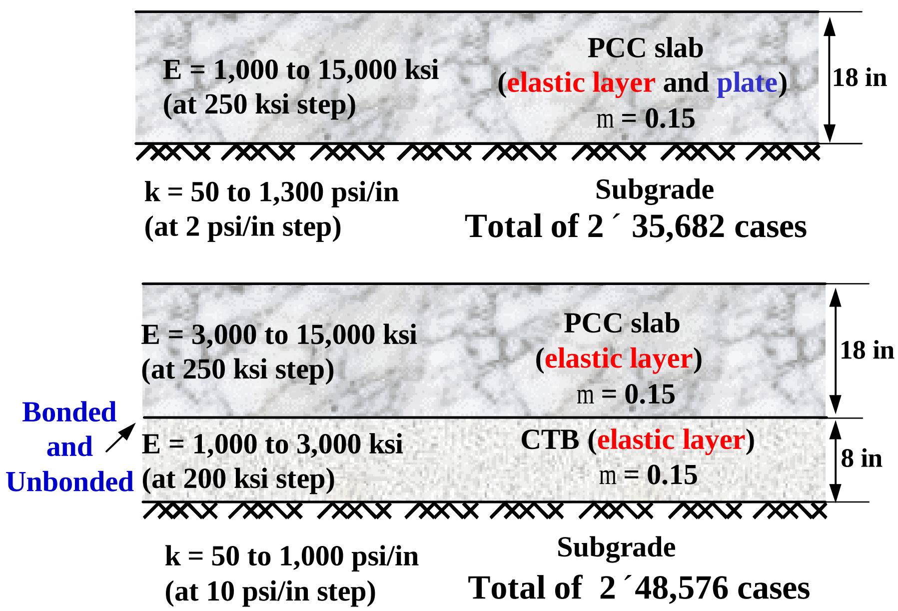

Figure 6. Factorial run performed with DIPLOMAT

BACKCALCULATION RESULTS

The database approach based on DIPLOMAT runs was tested against other backcalculation approaches. First, the methodology based on AREA is tested against solutions based on regression analysis developed by Hall (1992) and Ioannides *et al.* (1996). Then, the methodology based on individual deflections is tested using the database approach and an iterative approach (DIPLODEF). These comparisons were made for the 277 deflection basins collected at DIA. The concrete modulus of elasticity and k-values shown in this comparison represent the mean of all backcalculated results. The reason for this comparison is to validate the database approach developed herein. This section also presents the effect of different models, effect of different methodologies and effect of number of sensors on backcalculated pavement properties.

Validation of the Database Approach

Table 1 shows backcalculated mean values using the database approach and two regression equations to calculate the radius of relative stiffness based on AREA for four sensors at 0, 12 in, 24 in, and 36 in: Hall (1992) and Ioannides *et al.* (1996). It is observed that there is a maximum of 10 percent difference for the E-value and 25 percent for the k-value. There is also a difference in the backcalculated E and k-value when using Hall and Ioannides *et al.* regression equations. The reason for the difference is that they all are based on approximate solutions: both Hall and Ioannides *et al.* are based on regression analysis to estimate ℓ from AREA term and the Database approach selects ℓ from the calculated AREA terms that best matches with the measured AREA term. Therefore the difference between these solutions is only due to estimation of ℓ. Once ℓ is estimated, k-value can be estimated from Westergaard's closed-form solution and then E-value can be estimated from the radius of relative stiffness equation. There is more difference between estimated k-values than E-values because deflections are more sensitive to k-values than E-values.

Table 1. Comparison between AREA methodology

Parameter	Statistics	Database	Hall (1992)	Ioannides et al. (1996)
E_{slab}	Mean (psi)	2.70E+06	3.03E+06	2.81E+06
	COV (%)	37.1	34.4	35.0
k-value	Mean (psi/in)	665	759	818
	COV (%)	17.4	20.0	20.3

Table 2 shows a comparison between a database and an iterative approach using the methodology based on individual deflections measured from a total of 277 FWD tests using four sensors. Since the program DIPLODEF (Kothandram and Ioannides, 2001) had to be used several times, a user-friendly interface called IGEDIPLODEF (Input Generator and Extractor for DIPLODEF) was created using Visual Basic. This interface allows creating and extracting the results for all possible models allowable in DIPLODEF, which is a DOS-based program. When modeling two unbonded elastic layers over a dense liquid foundation, DIPLODEF only allowed a maximum slab modulus of elasticity of 8.25 Mpsi. This value was also used in the database approach in order to compare the two approaches. For the other cases, the range of elastic moduli and k-values used for DIPLODEF was the same shown in Figure 6. DIPLODEF was not used for backcalculation of an elastic layer over dense liquid because it aborted before finishing analysis. Kothandram (2000) reported the same problem with DIPLODEF.

As expected, the database developed in this paper produces very similar results as the program DIPLODEF since both DIPLODEF and database are based on the same program and use the individual deflections as the matching parameter. The agreement in the backcalculated results is remarkable considering no interpolation scheme was used in the database approach. The database approach described herein has demonstrated good agreement with the results from DIPLODEF and therefore offers an alternative backcalculation approach to problems that the current version of DIPLODEF is not capable of solving.

Table 2. Comparison between individual deflection methodologies

Model	Parameter	Database		DIPLODEF	
		Mean*	COV (%)	Mean*	COV (%)
1 plate	E_{slab}	5.22E+06	24.6	5.52E+06	24.1
	k-value	468	14.5	447	13.6
2 elastic layers (bonded)	E_{slab}	6.69E+06	27.5	6.60E+06	37.0
	E_{base}	2.03E+06	40.2	2.11E+06	39.7
	k-value	262	13.8	269	17.9
2 elastic layers (unbonded)	E_{slab}	7.68E+06	11.4	7.64E+06	14.5
	E_{base}	2.52E+06	24.4	2.90E+06	15.9
	k-value	356	12.4	360	20.3

* E in psi and k-value in psi/in.

Effect of Structure Modeling on Backcalculated Pavement Properties

In order to compare the effect of different models on backcalculated results, DIPLODEF and the database approach were used. DIPLODEF results were used only when the slab and base were modeled as one plate or two bonded elastic layers. The other two cases (one elastic layer and two unbonded elastic layers) could not be modeled with DIPLODEF and the database approach was applied to these cases. The moduli ranges used for both DIPLODEF and Database approaches during this analysis are shown in Figure 6.

Table 3 through Table 5 show the backcalculated E and k-values obtained using four individual sensor deflections for the various model types. Table 3 and Table 4 show the effect of the models on slab and base modulus of elasticity, respectively, whereas Table 5 shows this analysis for subgrade k-value. The concrete slab modulus of elasticity was found to be 65 percent higher on average when the pavement structure was modeled as a single elastic layer versus a single plate. The reason for this is because the plate theory used in DIPLOMAT (Kirchoff) ignores vertical and transverse shear deformations through the slab thickness, whereas the elastic layer theory considers such deformations. As a result, when using elastic layer theory, the vertical displacement at the surface will be greater than when the slab is modeled as plate, if the same pavement properties are used (see Figure 7). This difference decreases as the difference in distance between the point of interest to calculate displacement and the load location increases. Therefore, in order to reproduce the same deflection profile, layers modeled as elastic layer require greater values of elastic modulus than layers modeled as plate to compensate for higher deflections under the same load. Similarly, unbonded layers require higher surface layers moduli values to reproduce the same deflection as bonded layers. When both slab and base were modeled as elastic layers with an unbonded interface condition, the slab modulus was about 30 percent higher than in the bonded condition. The backcalculated surface modulus values are smaller when the slab system is stiffer (smaller surface deflections), i.e., backcalculated slab modulus is smaller when the slab is modeled as plate or bonded interface than when the slab is modeled as elastic layer or an unbonded interface.

Table 3. Comparison between slab modulus of elasticity for different models

Case	E_{slab} mean (psi)	E_{slab} std (psi)	COV (%)
1 plate	5.52E+06	1.33E+06	24.1
2 plates (bonded)	3.12E+06	1.12E+06	35.9
2 plates (unbonded)	5.39E+06	1.33E+06	24.7
1 elastic layer	8.64E+06	1.93E+06	22.4
2 elastic layers (bonded)	6.60E+06	2.44E+06	37.0
2 elastic layers (unbonded)	8.53E+06	1.87E+06	21.9

Table 4. Comparison between base modulus of elasticity for different models

Case	E_{base} mean (psi)	E_{base} std (psi)	COV (%)
1 plate	–	–	–
2 plates (bonded)	9.84E+05	3.74E+05	38.0
2 plates (unbonded)	1.44E+06	4.69E+05	32.6
1 elastic layer	–	–	–
2 elastic layers (bonded)	2.11E+06	8.39E+05	39.7
2 elastic layers (unbonded)	2.26E+06	6.82E+05	30.1

Table 5. Comparison between subgrade k-value for different models

Case	k mean (psi/in)	k std (psi/in)	COV (%)
1 plate	447	61	14
2 plates (bonded)	447	–	–
2 plates (unbonded)	447	–	–
1 elastic layer	328	49	15
2 elastic layers (bonded)	269	48	18
2 elastic layers (unbonded)	330	49	15

The backcalculation approach described by Ioannides and Khazanovich (1992) requires estimation of the ratio between the base and slab modulus of elasticity. Since there are numerous combinations of slab and base moduli values to produce the same modular ratio, a criterion had to be chosen. The criterion used was to keep the same ratio between base moduli values for unbonded and bonded conditions when slab and base are modeled as elastic layers and plates. It should be noted that the two elastic layers are not converted into one equivalent thickness or modulus as in the plate analysis. Therefore, the ratio between base and slab modulus were assumed to be the same as the backcalculated ratio moduli values when the layers were modeled as elastic layer. This allows comparison between bonded and unbonded conditions for the same slab model.

Modeling slabs as plates resulted in about 70 percent higher slab moduli values for unbonded compared to bonded conditions, as shown in Table 3. This is in agreement with the analysis of unbonded versus bonded elastic layers which resulted in higher slab moduli values for unbonded condition. However, using plate theory and the transformed section approach, the bonding condition between the base and slab has more effect on the average backcalculated elastic moduli of the slab than when the elastic layer theory is used to model the slab and base layer.

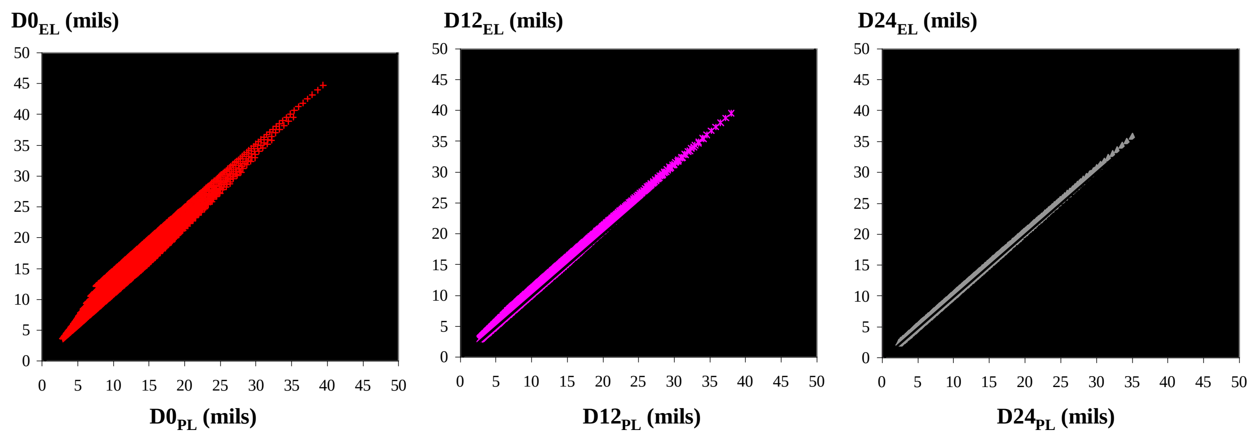

Figure 7. Comparison between surface deflections for slab as elastic layer and plate

Table 5 shows that higher backcalculated k-values are obtained when the slab is modeled as a plate instead of an elastic layer. The single plate model predicts 36 percent higher k-values compared with a single elastic layer. The k-value is increased by 66 percent for two bonded plates and about 35 percent for two unbonded plates relative to results obtained from modeling the slab and base as elastic layers. As discussed above, layers modeled as elastic layers result in higher backcalculated elastic slab modulus values than plates, since a higher modulus value is needed to account for the vertical compressibility and transverse shear deformation within the slab layer to match the same deflection experienced by a plate under the same circumstances. The concrete slab E-value is so high that a lower subgrade k-value is required in order to match deflections.

The average k-value is about 25 percent higher for the unbonded interface compared to a bonded interface when using elastic layers and two unbonded layers and one single layer produce similar k-values. It is interesting to notice that bonded condition result in lower subgrade k-value than unbonded condition, when slab and base are modeled as elastic layer. When the slab-base structure is modeled as a single plate, the k-value is not be affected by the interface condition because the elastic moduli values are selected to keep the same deflection profile according to the transformed layer concept. This is one limitation the current plate theory model has when trying to apply different interface conditions and determine the backcalculated soil k-value.

Effect of Methodology on Backcalculated Pavement Properties

The model of one plate over a dense liquid foundation was selected to evaluate the effect of different deflection basin parameters on backcalculated k-value, using four deflection sensors. Table 6 shows slab modulus of elasticity using all three different methodologies tested herein with the database backcalculation approach. It is observed that backcalculation based on individual deflections produce the highest slab modulus of elasticity mean value and the smallest coefficient of variation, whereas Actual Area methodology produces a slab modulus of elasticity mean between AREA and individual deflections methodologies. It is observed a very high coefficient of variation (about 40 percent) when backcalculating slab moduli values for both AREA and Actual Area methodologies.

Table 7 shows that similar k-value means are obtained when using the two approaches based on area of the deflection basin. In contrast, the methodology based on individual deflections produces the smallest mean k-value. Hall *et al.* (1996) also found that AREA methodology over predicts k-value compared to the Individual Deflection methodology. The Actual Area methodology also produces a very high coefficient of variation (37 percent) when backcalculating k-values. The high coefficient of variation must be associated with the fact that actual area is not a fundamental property, as AREA, which has a unique relationship with ℓ.

Table 6. Comparison between slab modulus of elasticity for different methodologies

Case	E_{slab} mean (psi)	E_{slab} std (psi)	COV (%)
AREA	2.70E+06	1.00E+06	37.1
Actual Area	3.72E+06	1.67E+06	44.9
Individual Deflections	5.22E+06	1.29E+06	24.6

Table 7. Comparison between subgrade k-value for different methodologies

Case	k mean (psi/in)	k std (psi/in)	COV (%)
AREA	665	116	17.4
Actual Area	700	259	36.9
Individual Deflections	468	68	14.5

Effect of Number of Sensors on Backcalculated Pavement Properties

The plate over dense liquid model was also selected for evaluating the effect of the different number of sensors on backcalculated pavement properties. Table 8 shows the effect of the different number of sensors on the backcalculated modulus of elasticity and k-value when using the AREA method. The number of sensors varied between 2 (minimum number to calculate deflection basin area) and 7 (maximum number of HWD sensors used for pavement evaluation). As the number of sensors increases, the mean value of modulus of elasticity increases and the mean value of modulus of subgrade reaction decreases. It is also observed that the coefficient of variation decreases, as the number of sensors increases. Hall *et al.* (1996) also shown that higher values of k are obtained when the number of sensors decreases. They also found that a smaller k-value is obtained if the sensor under the load is eliminated.

Table 9 shows the effect of the number of sensors on backcalculated modulus of elasticity and k-value, when the methodology based on individual deflections is applied. As expected, the use of only the maximum deflection (one sensor) does not provide the most consistent results, i.e., a very high coefficient of variation for the E and k-value prediction. The results in Table 9 show that a minimum of four sensors is necessary to produce a coefficient of variation of 25 percent or less and reasonable concrete slab modulus values. This is in agreement with current SHRP protocol, which recommends a seven-sensor arrangement for deflection measurements. Smith *et al.* (1997) show that the use of 'best fit' methodology that utilizes four sensors provides approximately the same backcalculated slab elastic moduli values as the AREA methodology that employs seven sensors. This finding is in agreement with the analysis presented herein. The k-value using four sensors based on individual deflection methodology is equivalent to use six sensors in the AREA methodology.

Table 8. Effect of different number of sensors on AREA methodology

Number of sensors	E_{slab}			k-value		
	Mean (psi)	Std (psi)	COV (%)	Mean (psi/in)	Std (psi/in)	COV (%)
2	1.28E+06	7.44E+05	58.3	1149	193	16.8
3	1.85E+06	9.13E+05	49.2	898	174	19.4
4	2.70E+06	1.00E+06	37.1	665	116	17.4
5	3.54E+06	1.12E+06	31.6	530	82	15.4
6	4.32E+06	1.27E+06	29.5	446	64	14.4
7	5.03E+06	1.43E+06	28.5	391	54	13.9

Table 9. Effect of different number of sensors on individual deflection methodology

Number of sensors	E_{slab}			k-value		
	Mean (psi)	Std (psi)	COV (%)	Mean (psi/in)	Std (psi/in)	COV (%)
1	6.57E+06	2.37E+06	36.1	399	208	52.1
2	1.92E+06	7.14E+05	37.2	1190	151	12.7
3	3.44E+06	1.13E+06	32.9	699	136	19.5
4	5.22E+06	1.29E+06	24.6	468	68	14.5
5	6.72E+06	1.49E+06	22.2	371	50	13.5
6	7.92E+06	1.54E+06	19.4	320	41	12.8
7	8.64E+06	1.38E+06	16.0	294	33	11.3

IN-SITU PAVEMENT PROPERTIES

The backcalculated results can vary significantly based on the model, methodology and number of sensors utilized. Previous work would suggest bonding and/or friction between the slab and base (Brill, 2000, Rufino *et al.*, 2001). The backcalculation results suggest the model with both base and slab as elastic layers may give the more realistic values for the slab modulus of elasticity and k-value when there is some friction between slab and base. The design report for the DIA was based on a static subgrade k-value of 150 psi/in. The subgrade soil at Denver was a low CBR, expansive clay. If the slab is modeled as a single plate or elastic layer then the subgrade k-value appears to be overestimated, although HWD testing is a dynamic impulse load which tends to double the apparent subgrade k-value (Dater *et al.*, 1994). A recent paper by Rufino *et al.* (2001) assumed no bonding between the slab-base interface, which resulted in an apparent overestimation of the k-value. This analysis also used a single peak deflection measurement to backcalculate the k-value from rolling aircraft loading over the concrete slabs. As shown above, a single sensor reading used in backcalculation can significantly overestimate the k-value of the soil and underestimate the apparent elastic modulus of the slab. Several other factors which were not considered in the backcalculation, which can have a significant affect are temperature curling during the HWD testing and the likelihood of a rigid layer within 10 ft of the surface.

CONCLUSIONS

A database-type backcalculation program called DATABACKDIPLO was developed to study the effect of different pavement modeling, backcalculation methodologies and number of sensors on backcalculated pavement properties. This program has been validated for some cases by comparing backcalculated pavement properties with DIPLODEF and some regression equations based on AREA. This study was based on 277 measured deflection basins selected from HWD testing performed at DIA for pavement evaluation. Some of the findings obtained from this study are listed as follows:

- The effect of pavement structure modeling (layer and interface modeling) is crucial when backcalculating pavement properties. Backcalculated slab modulus of elasticity is lower on average when the pavement layers on top of subgrade are bonded versus unbonded interface or plate compared to elastic layer. Layer modeling (elastic layer versus plate) affects backcalculated slab moduli values about twice as much the interface modeling (unbonded versus bonded) when slab and base layers are modeled as elastic layers. When the slab and base layers are modeled as plates, the interface condition has more effect on backcalculate slab moduli values than when the layers are modeled as elastic layers: about 70 percent compared to 30 percent.
- Higher backcalculated k-values are obtained when the slab is modeled as plate compared to modeling the slab as elastic layer. This effect is greater when pavement layers are modeled as bonded elastic layers than when pavement layers are modeled as unbonded elastic layers or only one elastic layer. The higher backcalculated k-values are necessary for layers modeled as plates to maintain the same deflection profile when compared to layers modeled as elastic layers. However, unbonded interface conditions require not only higher moduli values but also higher k-values when both slab and base layers are modeled as elastic layers.
- The selection of methodology is also important. It is observed that backcalculation based on individual deflections produce higher slab modulus of elasticity and smaller k-value mean values than the AREA method. In order to converge to a more realistic backcalculated solution, a minimum of seven sensors should be used in the AREA methodology and a minimum of four sensors for the individual deflection methodology. Backcalculated properties based on Actual Area methodology have a very high coefficient of variation (about 40 percent) that is associated with Actual Area not being a fundamental property, as AREA.
- The number of sensors can also significantly affect backcalculated properties: as the number of sensors increases, the mean values of modulus of elasticity increases and the mean values of modulus of subgrade reaction decreases. It is also observed that the coefficient of variation decreases, as the number of sensors increases. In future analysis from DIA data, it is worthwhile to use entire deflection history to backcalculate pavement properties from different aircraft to avoid errors associated with insufficient description of the deflection basin.
- Modeling of the slab and base as elastic layers appear to give more reasonable backcalculated results since the interface bonding condition can be reflected both in the backcalculated slab elastic modulus and subgrade k-value.

ACKNOWLEDGMENTS/DISCLAIMER

This paper was prepared from a study conducted in the Center of Excellence for Airport Pavement Research funded by the Federal Aviation Administration under Research Grant Number 95-C-001. The contents of this paper reflect the views of the authors who are responsible for the facts and accuracy of the data presented within. The contents do not necessarily reflect the official views and policies of the Federal Aviation Administration. This paper does not constitute a standard, specification, or regulation.

REFERENCES

Barenberg, E. J., and K. A. Petros, 1991. "Evaluation of Concrete Pavements Using NDT Results," Project IHR-512, University of Illinois at Urbana-Champaign and Illinois Department of Transportation, Report No. UILU-ENG-91-2006.

Brill, D. R., 2000. "Field Verification of a 3D Finite Element Rigid Airport Pavement Model," Report No. DOT/FAA/AR-00/33, U.S. Department of Transportation, Federal Aviation Administration, Office of Aviation, Washington, DC.

Darter, M.I., K.T. Hall, and C.M. Kuo, 1994. "Support under Concrete Pavements," National Cooperative Highway Research Program 1-30, Transportation Research Board.

Darter, M.I., K.T. Hall, and C.M. Kuo, 1995. "Support under Portland Cement Concrete Pavements," Report 372, National Cooperative Highway Research Program, Transportation Research Board.

Dong, M., and G. F. Hayhoe, 1999. "Denver International Airport Sensor Processing and Database," Report DOT/FAA/AR-9/, U.S. Department of Transportation, Federal Aviation Administration, Washington, DC, January.

Foxworthy, P. T., and M. I. Darter, 1989. "ILLI-SLAB and FWD Deflection Basins for Characterization of Rigid Pavements," Nondestructive Testing of Pavements and Backcalculation of Moduli, A. J. Bush III and Y. Baladi Editors, American Society for Testing and Materials, pp. 368-386.

Hall, K. T., 1992. "Backcalculation Solutions for Concrete Pavements," Technical Memo Prepared for SHRP Contract P-020, Long-Term Pavement Performance Data Analysis.

Hall, K. T., M. I. Darter, T. Hoerner, and L. Khazanovich, 1996. "LTPP Data Analysis – Phase I: Validation of Guidelines for K Value Selection and Concrete Pavement Performance Prediction," Interim Report prepared for FHWA, ERES Consultants, Champaign, IL.

Harrison, J. A., 1997. *Analysis of Rigid Pavement Response Data Induced by Military Aircraft at Denver International Airport*, Master thesis, Mississippi State University, Mississippi, USA.

Hoffman, M. S. and M. R. Thompson, 1981. "Mechanistic Interpretation of Nondestructive Pavement Testing Deflections," Report No. FHWA/IL/UI-190, Transportation Engineering Series No. 32, Illinois Cooperative Highway and Transportation Research Series No. 190, University of Illinois at Urbana-Champaign.

Ioannides, A. M., 1984. *Analysis of Slabs-on-Grade for a Variety of Loading and Support Conditions*, Ph.D. dissertation, University of Illinois, Illinois, USA.

Ioannides, A. M., 1990. "Dimensional Analysis in NDT Rigid Pavement Evaluation," Journal of Transportation Engineering, Vol.116, No. 1, pp.23-36.

Ioannides, A. M., E. J. Barenberg, and J. A. Lary, 1989. "Interpretation of Falling Weight Deflectometer Results Using Principals of Dimensional Analysis," Proceedings, 4th International Conference on Concrete Pavement Design and Rehabilitation, Purdue University, pp.231-247.

Ioannides, A.M., 1991. "Subgrade Characterization for Portland Cement Concrete Pavement Systems", Proceedings, International Conference on Geothecnical Engineereing for Coastal Development – Theory and Practice, Port and Habour Institute, Ministry of Transport, Yokohama 3-6 Sep., Japan, pp.809-814.

Ioannides, A.M., 1994. "Concrete Pavement Backcalculation Using ILLI-BACK 3.0," Nondestructive Testing of Pavements and Backcalculation of Moduli, Vol. 2, A. J. Bush III and Y. Baladi Editors, American Society for Testing and Materials, pp. 103-124.

Ioannides, A.M., and L. Khazanovich, 1992. "Backcalculation Procedure for Three Layers Concrete Pavements," Proceedings, Fourth International Conference on Bearing Capacity of Roads and Airfields, Mineapolis, MN, pp. 1-14.

Ioannides, A.M., D. R. Alexander, M. I. Hammons, and G. M. Davis, 1996. "Application of Artificial Neural Networks to Concrete Pavement Joint Evaluation," *Transportation Research Record 1540,* Transportation Research Board, pp. 56-64.

Ioannides, A.M., L. Khazanovich, and J.L. Becque, 1992. "Structural Evaluation of Base Layers in Concrete Pavement Systems," Transportation Research Record 1370, Transportation Research Board, pp. 20-28.

Khazanovich, L., 1994. *Structural Analysis of Multi-Layered Concrete Pavement Systems,* Ph.D. dissertation, University of Illinois, Illinois, USA.

Khazanovich, L., and A.M. Ioannides, 1993. "Finite Element Analysis of Slabs-on-Grade Using Higher Order Subgrade Soil Models," Proceedings, ASCE Specialty Conference on Airport Pavement Innovations – Theory to Practice, Waterways Experiment Station, Vicksburg, MS, pp.16-30.

Khazanovich, L., and A.M. Ioannides, 1995. "DIPLOMAT: Analysis Program for Bituminous and Concrete Pavements," Transportation Research Record 1482, Transportation Research Board, pp. 52-60.

Khazanovich, L., and J. Roesler, 1997. "DIPLOBACK: Neural-Network-Based Backcalculation Programs for Composite Pavements," Transportation Research Record 1570, Transportation Research Board, pp.143-150.

Korovesis, G. T., 1990. *Analysis of Slabs-on-Grade fo Pavement Systems for a Subjected to Wheel and Temperature Loadings,* Ph.D. dissertation, University of Illinois, Illinois, USA.

Kothandram, S, 2000. "Backcalculation of Layer Moduli for Asphalt and Concrete Pavements," M. S. Thesis, Department of Civil and Environmental Engineering, University of Cincinnati, OH.

Kothandram, S., and A. M. Ioannides, 2002. "DIPLODEF: A Unified Backcalculation System for Asphalt and Concrete Pavements," Transportation Research Record 1764, Journal of the Transportation Research Board, Transportation Research Board, pp. 20-29.

Losberg, A., 1960. "Structurally Reinforced Concrete Pavements," Doktorsavhandlingar Vid Chalmers Tekniska Hogskola, Goteborg, Sweden.

Mahoney, J. P., N. F. Coetzee, R. N. Stubstad, R. N., and S. W. Lee, 1989. "A Performance Comparison of Selected Backcalculation Computer Programs," Nondestructive Testing of pavements and Backcalculation of Moduli, A. J. Bush III and Y. Baladi Editors, American Society for Testing and Materials, pp. 452-469.

Rufino, D., J. Roesler, E. Barenberg, and E. Tutumluer, 2001. "Analysis of Pavement Responses to Aircraft and Environmental Loading at Denver International Airport," *Proceedings, 7th International Conference on Concrete Pavements,* Orlando, Florida, September, pp.747-761.

Smith, K. D., M. J. Wade, D. G. Peshkin, L. Khazanovich, H. T. Yu, and M. I. Dater, 1997. "Performance of Concrete Pavements," Volume II – Evaluation of In-Service Concrete Pavements, Report No. FHWA-RD-95-110, ERES Consultants, Champaign, IL.

Tabatabaie, A.M., and E.J. Barenberg, 1978. "Finite Element Analysis of Jointed or Cracked Concrete Pavements," *Transportation Research Record 671,* Transportation Research Board, pp. 11-18.

Ullidtz, P., Battiato, G., Larsen, B. K., and Stubstad, R. N., 1987. "Verification of the Analytical-Empirical Method of Pavement Evaluation Based on FWD Testing," Proceedings, Sixth International Conference on Structural Design of Asphalt Pavements, The University of Michigan, Ann Arbor, MI, pp. 521-532.

Van Cauwelaert, F. J., D. R. Alexander, T. D. White, and W. R. Barker, 1989. "Multilayer Elastic Program for Backcalculating Layer Moduli in Pavement Evaluation," Nondestructive Testing of Pavements and Backcalculation of Moduli, A. J. Bush III and Y. Baladi Editors, American Society for Testing and Materials, pp. 171-188.

Westergaard, H.M., 1926. "Stresses in Concrete Pavements Computed by Theoretical Analysis," Public Roads, Vol. 07, pp. 25-35.

Winkler, E., 1867. "Die Lehre von der Elastizitat and Festigkeit," (The Theory of Elasticity and Stiffness), H. Dominicus, Prague, Czechoslovakia.